λ/4-air gap/semiconductor Bragg reflectors on GaN based laser diodes

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Focused Ion Beam (FIB) etching was used to form λ/4-air gap/semiconductor Bragg reflectors on GaN/InGaN laser diodes. We report on the fabrication method and results for a single 5λ/4 air gap and 5λ/4 mesa used as one of the Fabry-Perot cavity mirrors. A reduction in threshold current could be attributed to the enhanced reflectivity with respect to a cleaved facet.

Introduction

In this report we combine FIB etching technology (already shown successful in forming simple Fabry-Perot cavity mirrors on GaN based injection laser[1]), with the concept of λ/4-air gap/semiconductor Bragg reflectors (used for example to achieve low critical current densities in GaInAsP/InP short cavity laser[2]). For applications where geometry or other factors prohibit the deposition of high reflectivity dielectric mirrors, such a technique may be beneficial.

Although in principle multiple periods of air gap/semiconductor unit are necessary for generating a useful increase in reflectivity[3], we demonstrate here a proof of concept using only a single air gap as one of the mirrors as shown in Fig. 1.

Fabrication process

The multi-quantum well laser structure was grown on a sapphire (0001) substrate by metalorganic chemical vapor phase epitaxy. It consisted of a low-temperature deposited GaN buffer layer about 25nm thick, a 4μm GaN:Si layer followed by a 2μm highly doped n-type GaN:Si layer, a ~1nm InGaN:Si layer, a 0.6μm thick 150 period $Al_{0.1}Ga_{0.9}N$:Si/GaN:Si superlattice structure (SLS) as a cladding layer, a 100nm thick n-GaN:Si optical guiding layer, an InGaN/GaN 2.5nm/5nm triple quantum well active layer, a ~1nm p-$Al_{0.1}Ga_{0.9}N$:Si/GaN:Mg anti-diffusion layer, a 100nm thick p-GaN:Mg optical guiding layer, a 0.6μm 150 period p-AlGaN/p-GaN:Mg SLS cladding layer, and finally a p-GaN:Mg contact layer 0.15μm thick. P-type Mg acceptor activation was achieved using a 20 minute anneal in a 9:1 N_2:O_2 atmosphere. Using standard lithography techniques and BCl_3-based reactive ion etching (RIE), a 10μm ridge for lateral optical confinement was formed above a 50μm wide mesa. A Ni/Au 250Å/250Å p-contact was deposited on the ridge and annealed at 500°C in air for 10 minutes. The remainder of the mesa surface was isolated with 1200Å of SiO_2 for the final 50μm wide 3500Å thick gold pad. The n-contact consisted of a Ti/Al 250Å/3500Å deposited layer annealed in N_2 at 450°C for 30 minutes. After mechanically polishing the substrate down to a thickness ~70μm, laser cavities were formed by cleaving in the sapphire $<11\bar{2}0>$ directions. The current-voltage and emission power characteristics of the laser diodes were measured prior to FIB etching. Also before etching the actual reflectors, most of the contact pad material around the mirror area was removed by etching 4000Å deep in a 30μm x 25μm area. Following this first a 30μm x 16μm area 2μm deep was etched using relatively high ion beam current (182pA with a 350Å spot size). Then a 30μm x 16μm area was etched 2μm deep at low beam current (11pA with a 150Å spot size). Finally, the mirror was formed by etching away two 15μm x 0.5μm boxes, one from the edge, the other offset

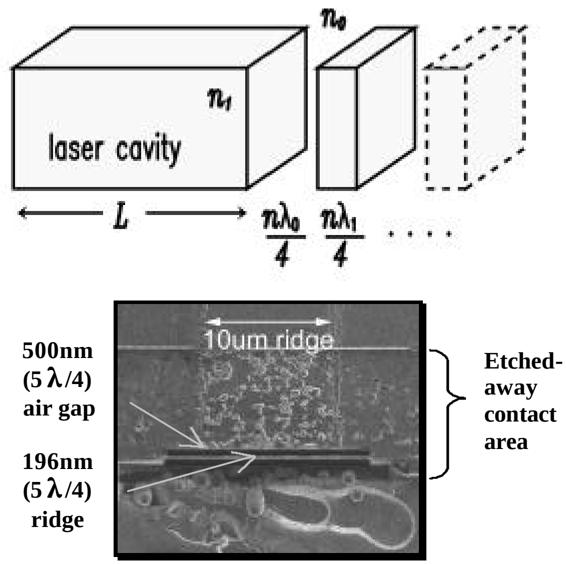

Fig. 1 The top diagram shows the conceptual design of a λ/4-air gap/semiconductor Bragg reflector implemented as one mirror of a Fabry-Perot cavity. The bottom electron microscope picture is a top-view of one of the actual FIB etched reflector.

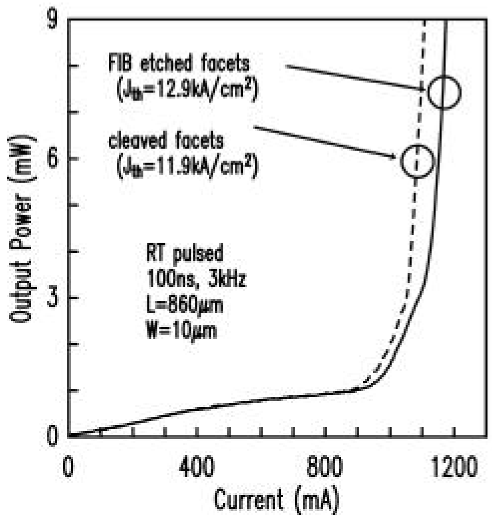

Fig. 2 Light output power versus pulse injected current characteristics for a laser diode, before and after the formation of FIB etched facets.

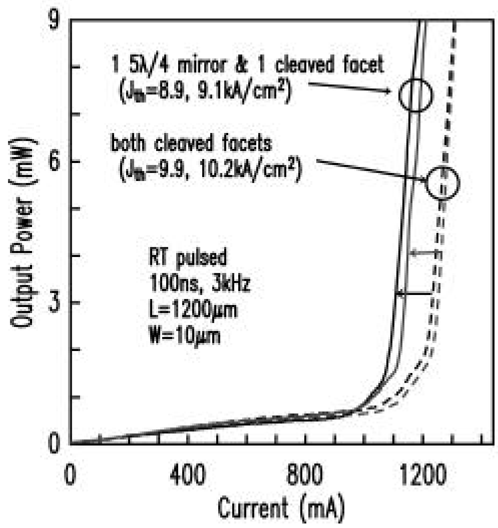

Fig. 3 Light output power versus pulse injected current characteristics for a laser diode, before and after the formation of single FIB etched 5 λ /4-air gap/semiconductor Bragg reflector facet.

along the cavity to form a 5λ/4 air gap and a 5λ/4 mesa as shown in Fig. 1. Each of the three etch step required about 3 hours. The required gap and reflector mesa dimensions were calculated using the peak of the laser emission λ =400nm and an index of refraction *n*=2.55.

Results and discussion

In order to verify that mirror facets could indeed be realized by FIB etching on our structures, we first made one laser diode with FIB etched facets. The method was the same as described above, omitting the air gap region, but forming facets at both ends of the 860μm cavity. The results for output power versus injection current are shown in Fig. 2. The dotted curve corresponds to the diode with cleaved facets. This same diode was then used to form the FIB etched facets. A slight increase in the threshold current density from 11.9kA/cm^2 to 12.9kA/cm^2 could be due to increased mirror roughness or from slightly non-vertical etched walls.

The results for two laser diodes of identical 1200μm cavity length, on both of which a single 5λ/4-air gap/semiconductor Bragg reflector was used as one of the mirrors, are shown in Fig. 3. As above, the dotted curves correspond to the cleaved facet lasers before FIB mirror formation. Consistently, for both samples a clear drop in the critical current was measured, from 9.9kA/cm^2 to 8.9kA/cm^2 and from 10.2kA/cm^2 to 9.1kA/cm^2, after the formation of the air gap structure. From the results of the FIB facetted laser diode shown in Fig. 2, we attribute this reduction to the presence of the air gap structure and not to an improvement in facet quality. Assuming a reflectivity of 19% for the cleaved facets, the increase in J_{th} for the simple FIB etched facets corresponds to a reduction to 16.5% reflectivity. The reduction in J_{th} shown in Fig. 3 corresponds to a 27% reflectivity on the air gap mirror side, an increase of 65%.

Conclusions

We demonstrated the concept of using λ /4-air gap/semiconductor Bragg reflectors as Fabry-Perot cavity mirrors in GaN based current injection laser diodes. This was done by FIB etching a single 5λ/4 air gap and leaving a 5λ/4 semiconductor wide structure as one of the cavity mirrors. The results on two samples of equal cavity length showed a consistent improvement in the threshold current. This improvement, corresponding to an effective single mirror reflectivity increase of 65% could be attributed to the formation of the air-gap structure.

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References

[1] H. Katoh, T. Takeuchi, C. Anbe, R. Mizumoto, S. Yamaguchi, C. Wetzel, H. Amano, I. Akasaki, Y. Kaneko and N. Yamada, Jpn. J. Appl. Phys. **37** (1998) L444.
[2] M.M. Raj, K. Numata, S. Toyoshima and S. Arai, Jpn. J. Appl. Phys. **37**, (1998) L1461
[3] K-C Shin, M. Tamura, A. Kasukawa, N. Serizawa, S. Kurihashi, S. Tamura and S. Arai, IEEE Photon. Technol. Lett. **7** (1995) 1119.